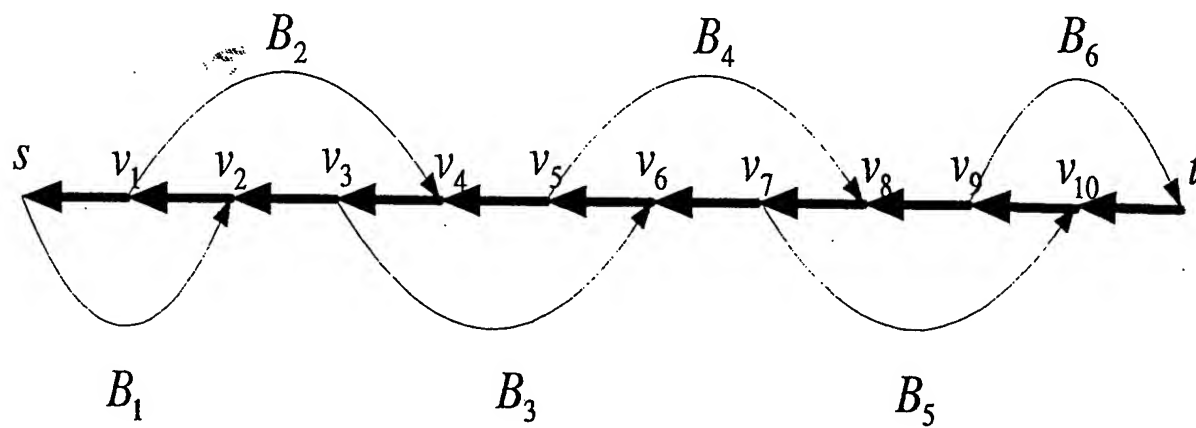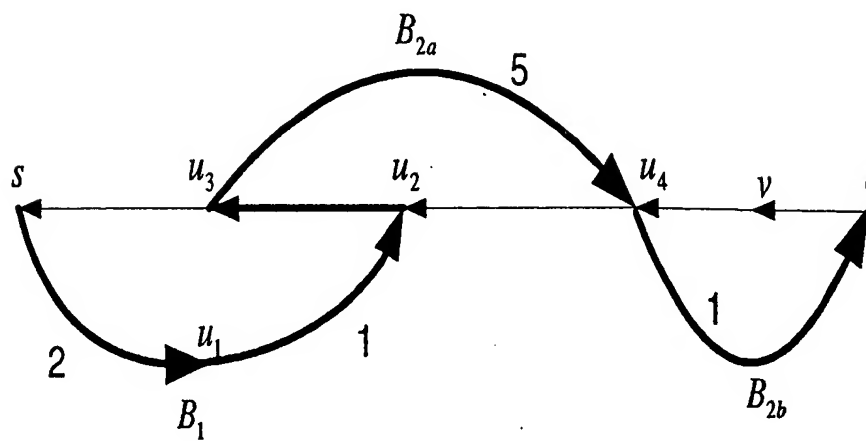FIGURE 1

FIGURE 2

FIGURE 3

Algorithm PP $(G(V,E), \hat{\mathcal{P}}, \hat{d}, U)$

    parameters:

      $G(V,E)$ - network,

      $\{d_l, c_l\}_{l \in E}$ - delays and costs of the network links,

      $\hat{\mathcal{P}} = \{s = v_0, v_1, ..., t = v_n\}$ - QoS path,

      $\hat{d}$- delay constraint,

      U- the upper bound on the cost of $\mathcal{R}$.

1    $\Delta \leftarrow \hat{d} - D(\hat{\mathcal{P}})$

2    $E' \leftarrow E$

3   for each link $l = (v_i, v_{i+1}) \in \hat{\mathcal{P}}$ do

4      $E' \leftarrow E' \setminus \{(v_i, v_{i+1}) \in \hat{\mathcal{P}}\}$

5      $E' \leftarrow E' \cup \{(v_{i+1}, v_i) \in \hat{\mathcal{P}}\}, c_{(v_{i+1}, v_i)} \leftarrow 0$

6   for all $v_i \in V$ do

7      $D_{v_i}[0] \leftarrow \infty$

8    $D_s[0] \leftarrow 0$

9   for $c = 1, 2, ..., U$ do

10   for each $v_j \in V$ in order such that v_j is before $v_{j'}$ if v_j is a successor of $v_{j'}$ in $\hat{\mathcal{P}}$ do

11       $D_{v_j}[c] \leftarrow D_{v_j}[c-1]$

12   for each link $l = (v_i, v_j) \in E'$ do

13   RELAX$(l(v_i, v_j), c, \Delta)$

14   if $D_t[c] \leq D(\hat{\mathcal{P}})$ then

15   determine walk $\mathcal{W}$ by backtracking

16   return $\mathcal{W}$.

17   return FAIL

    Procedure RELAX $(l = (v_i, v_j), c, \Delta)$

1   if $v_j \in \hat{\mathcal{P}}$ and $v_i \in \hat{\mathcal{P}}$ then

2   if $D_{v_i}[c] \leq D(\hat{\mathcal{P}}_{(s,v_i)})$ then

3      $D_{v_j}[c] \leftarrow \min\{D_{v_j}[c], D(\hat{\mathcal{P}}_{(s,v_j)})\}$

4   else

5   if $c_l \leq c$ then

6      $D_{v_j}[c] \leftarrow \min\{D_{v_j}[c], D_{v_i}[c - c_l] + d_l)\}$

7   if $v_j \in \hat{\mathcal{P}}$ and $D_{v_j}[c] \leq D(\hat{\mathcal{P}}_{(s,v_j)}) + \Delta$ then

8     $D_{v_j}[c] \leftarrow \min\{D_{v_j}[c], D(\hat{\mathcal{P}}_{(s,v_j)})\}$

FIGURE 4

Algorithm RT $(G(V,E), \hat{\mathcal{P}}, \hat{d}, \varepsilon)$

    parameters:

      $G(V,E)$ - network

      $\hat{\mathcal{P}} = \{s = v_1, v_2, ..., t = v_n\}$ - QoS path,

      $\hat{d}$- delay constraint

      ε- approximation ratio

1 $L, U \leftarrow$ BOUND$(G(V,E), \hat{\mathcal{P}}, \hat{d})$
2 do
3    $B \leftarrow \sqrt{L \cdot U}$
4   if TEST$(G(V,E), \hat{\mathcal{P}}, \hat{d}, B, \varepsilon)$ returns YES then
5      $L \leftarrow B$
6   else
7      $U \leftarrow 2 \cdot B$
8 until $U/L \leq 8$.
9 $\mathcal{W} \leftarrow$ SCALE$(G(V,E), \hat{\mathcal{P}}, \hat{d}, L, U, \varepsilon)$
10 return the restoration topology that corresponds to $\mathcal{W}$.

    Procedure SCALE$(G(V,E), \hat{\mathcal{P}}, \hat{d}, L, U, \varepsilon)$
1 $S \leftarrow \frac{L\varepsilon}{2N}$
2 for each link $l \in E$ do
3    $c'_l \leftarrow \lfloor \frac{c_l}{S} \rfloor + 1$
4 $\tilde{U} \leftarrow \lfloor \frac{U}{S} \rfloor + 2N$
5 return PP$(G(V,E), \{d_l, c'_l\}_{l \in E}, \hat{\mathcal{P}}, \hat{d}, \tilde{U})$

    Procedure TEST$(G(V,E), \hat{\mathcal{P}}, \hat{d}, B)$
1 Apply Procedure SCALE for $(G(V,E), \hat{\mathcal{P}}, \hat{d}, B, B, 2)$
2 if Algorithm SCALE returned FAIL then
3   return NO
4 else
5   return YES

    Procedure BOUND$(G(V,E), \hat{\mathcal{P}}, \hat{d})$
1 let $c^1 < c^2 < \cdots < c^r$ the distinct costs values of the links.
2 $low \leftarrow 1; high \leftarrow r$
3 while $low < high - 1$
4    $j \leftarrow \lfloor (high + low)/2 \rfloor$
5    $E' \leftarrow \{l \mid c_l \leq c^j\}$
6   set $c_l \leftarrow 1$ for each $l \in E'$
7   apply Algorithm PP on $(G'(V, E'), \hat{\mathcal{P}}, \hat{d}, 2N)$
8   if Algorithm PP returned FAIL then
9      $high \leftarrow j$
10   else
11     $low \leftarrow j$
12 $U \leftarrow 2N \cdot c^{high}; L \leftarrow c^{high};$
13 return $L, U;$

FIGURE 5
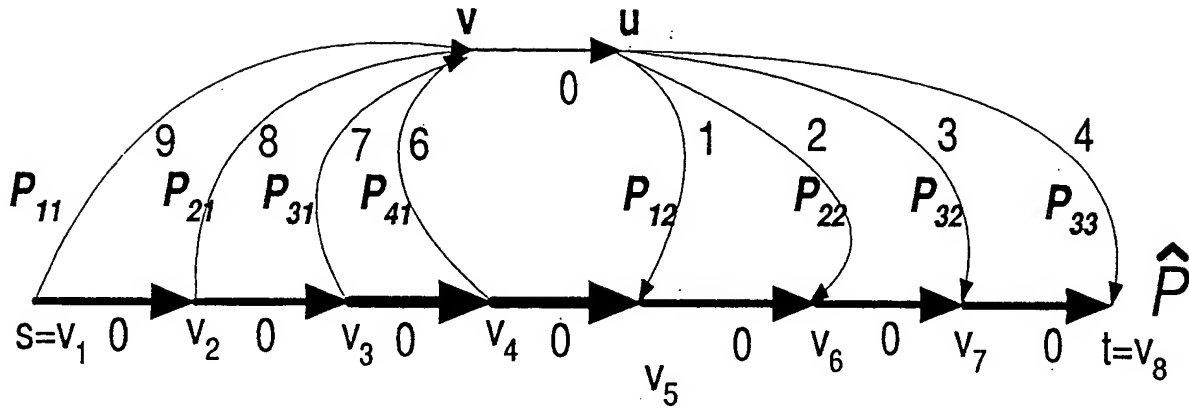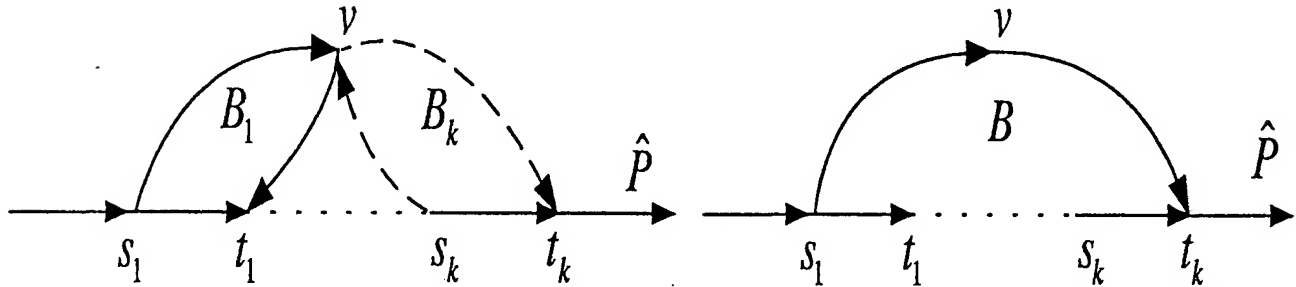
FIGURE 6

FIGURE 7

Algorithm DRT $(G(V,E), \hat{P}, \hat{d}, \varepsilon)$

    parameters:

      $G(V,E)$ - network

      $\hat{P} = \{s = v_1, v_2, ..., t = v_n\}$ - QoS path,

      $\hat{d}$- delay constraint

      ε- approximation ratio

1   $\hat{d}' \leftarrow 2\hat{d} - D(\hat{P})$

2   $L, U \leftarrow$ BOUND$(G(V,E), \hat{P}, \hat{d}')$

3 **do**

4     $B \leftarrow \sqrt{L \cdot U}$

5   Apply Procedure SCALE for $G(V,E), \hat{P}, \hat{d}', B, B, \varepsilon)$

6   **if** Procedure SCALE return FAIL **then**

7       $L \leftarrow B$

8   **else**

9   Set $\mathcal{W}$ be the walk returned by Procedure SCALE

10   **if** $C(\mathcal{W}) \leq L$ **then**

11   **return** the restoration topology $\mathcal{R}$ that corresponds to $\mathcal{W}$.

12   **else**

13       $U \leftarrow 2 \cdot B,$

14 **until** $U/L \leq 8$.

15 Apply Procedure SCALE for $(G(V,E), \hat{P}, \hat{d}', L, U, \varepsilon)$

16 **if** Procedure SCALE does not fail **then**

17   Set $\mathcal{W}$ be the walk returned by Procedure SCALE

18 **return** the restoration topology $\mathcal{R}$ that corresponds to $\mathcal{W}$.

FIGURE 8

| Primary Path Generator 905 | Auxiliary Graph Generator 920 | Walk Identifier 930 | Bridge 940 Identifier |

900

s ⟶ t 915

s ⟵ t 925

s w t 935

s t 945

Start
1010

↓

Identify Primary Path

1015

↓

Construct Auxiliary Graph

1020

↓

Identify one or more walks

1030

↓

Identify bridges such that each link is protected

1035

↓

End
1040